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AI-Driven Early Detection of Gastric Ulcers Using High-Resolution Imaging and Multi-Scale Radiomic Feature Analysis

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Abstract

Gastric ulcers are a major gastrointestinal disorder whose early diagnosis remains challenging because conventional endoscopic assessment is subjective and prone to inter-observer variability. Recent advances in artificial intelligence (AI) and medical image analysis provide promising opportunities for improving diagnostic accuracy and enabling reliable early detection. This study proposes an AI-driven framework for early gastric ulcer detection using high-resolution endoscopic imaging and multi-scale radiomic feature analysis.

The proposed system integrates deep learning–based hierarchical feature extraction with handcrafted radiomic descriptors to capture both global semantic information and subtle mucosal abnormalities associated with ulcerative lesions. Convolutional neural networks (CNNs) are employed to learn discriminative visual representations, while multi-scale radiomic analysis quantifies texture heterogeneity, intensity variation, and morphological irregularities. An attention-guided fusion mechanism is further introduced to adaptively combine deep and radiomic features according to their diagnostic relevance. Extensive experiments were conducted using a curated dataset of high-resolution gastric endoscopic images with preprocessing, augmentation, and cross-validation strategies. The proposed framework outperformed radiomics-only, deep learning–only, and conventional hybrid baseline models across multiple evaluation metrics, including accuracy, sensitivity, specificity, F1-score, and area under the curve (AUC). Ablation analysis additionally confirmed the importance of multi-scale radiomics and attention-based fusion in improving diagnostic robustness and generalization. The results demonstrate that combining deep learning with multi-scale radiomic analysis provides a robust and interpretable solution for early gastric ulcer detection. The proposed framework shows strong potential as a clinical decision-support system capable of improving diagnostic consistency, facilitating early intervention, and enhancing patient outcomes.

Keywords

Gastric Ulcer Detection; Artificial Intelligence; Deep Learning; High-Resolution Endoscopic Imaging; Multi-Scale Radiomic Feature Analysis; Computer-Aided Diagnosis.

1. Introduction

Gastric ulcers remain one of the most prevalent and clinically significant gastrointestinal disorders worldwide, contributing substantially to morbidity, healthcare burden, and reduced quality of life. These lesions arise from localized disruption of the gastric mucosal barrier and are strongly associated with *Helicobacter pylori* infection, chronic non-steroidal anti-inflammatory drug (NSAID) use, physiological stress, smoking, alcohol consumption, and various systemic disorders. Although gastric ulcers are generally manageable when diagnosed at an early stage, delayed detection may lead to serious complications including gastrointestinal bleeding, perforation, gastric outlet obstruction, and malignant transformation. Consequently, timely and accurate identification of gastric ulcers is essential for effective therapeutic intervention and improved clinical outcomes [1-2].

Upper gastrointestinal endoscopy is currently regarded as the gold-standard diagnostic modality for gastric ulcer assessment because it enables direct visualization of the gastric mucosa and targeted biopsy collection. However, conventional endoscopic interpretation largely depends on the expertise and subjective judgment of clinicians, making diagnostic performance vulnerable to inter-observer variability, fatigue, examination conditions, and differences in imaging quality. Early-stage gastric ulcers frequently appear as subtle mucosal erosions, minor discolorations, shallow depressions, or faint texture irregularities that are difficult to identify consistently during routine examination. Furthermore, variations in illumination, endoscopic devices, patient anatomy, and acquisition protocols introduce additional diagnostic complexity, increasing the likelihood of missed lesions and delayed clinical decision-making. These limitations highlight the urgent need for intelligent computer-aided diagnostic systems capable of providing objective, reproducible, and clinically reliable assistance during endoscopic evaluation [3-4].

Recent advances in artificial intelligence (AI), particularly deep learning, have revolutionized medical image analysis by enabling automated feature extraction and high-level pattern recognition directly from imaging data. Convolutional neural networks (CNNs) and their advanced variants have demonstrated remarkable performance in numerous gastrointestinal imaging applications, including polyp detection, bleeding localization, gastric cancer classification, lesion segmentation, and ulcer identification. By learning hierarchical spatial representations from raw image inputs, deep learning frameworks can identify complex visual patterns beyond conventional human perception. Modern architectures such as ResNet, DenseNet, EfficientNet, InceptionNet, and transformer-based hybrid networks have further improved diagnostic accuracy through enhanced representation learning and contextual feature modeling. Attention mechanisms incorporated within these architectures enable the model to focus selectively on diagnostically important regions, thereby improving localization and classification performance in challenging endoscopic scenarios [5-7].

Despite their promising performance, deep learning–based systems face several limitations that restrict their broader clinical adoption. Most models operate as black-box frameworks with limited interpretability, reducing clinician trust and hindering transparent medical decision-making. Additionally, deep learning models are highly dependent on large annotated datasets and are often sensitive to domain shifts arising from variations in imaging equipment, illumination conditions, patient populations, and acquisition protocols. Another important challenge involves the detection of subtle early-stage gastric ulcer characteristics, which frequently manifest as fine-grained textural and morphological abnormalities that may not be adequately emphasized within global deep feature representations optimized primarily for classification accuracy. Table 1 presents a comparative overview of major gastric ulcer detection paradigms, highlighting their feature representations, strengths, and associated limitations.

Table 1. Comparative Analysis of Gastric Ulcer Detection Paradigms

Diagnostic Paradigm	Feature Representation	Key Advantages	Major Limitations

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28

https://scientia-nexus.org/index.php/jpcs
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Conventional Endoscopy	Visual inspection	Real-time assessment; clinical familiarity	Subjective interpretation; high variability; early lesions often missed
Deep Learning–Based Models	Learned hierarchical features	High accuracy; automated learning; scalability	Limited interpretability; sensitivity to data bias
Radiomics-Based Models	Handcrafted quantitative features	Interpretability; sensitivity to texture and morphology	Manual feature engineering; limited adaptability
Hybrid DL–Radiomics (Existing)	Combined deep + radiomic features	Improved performance over single-method models	Simple fusion; lack of adaptive weighting
Proposed Framework	Deep + multi-scale radiomics with attention	High accuracy; robustness; interpretability; adaptive fusion	Increased computational demand

Radiomics has emerged as a complementary computational paradigm capable of addressing several of these limitations by extracting quantitative handcrafted descriptors related to texture, intensity, shape, and spatial heterogeneity from medical images. Unlike purely data-driven deep learning approaches, radiomic features provide interpretable and biologically meaningful information that can capture subtle tissue phenotypes associated with pathological transformation. Multi-scale radiomic analysis further enhances lesion characterization by evaluating image patterns across multiple spatial resolutions, enabling improved sensitivity to microstructural abnormalities and localized mucosal changes. However, radiomics-based systems alone are constrained by limited representational flexibility, handcrafted feature dependency, and challenges associated with optimal feature selection and generalization [8].

To overcome these limitations, recent research increasingly emphasizes hybrid AI frameworks that integrate deep learning representations with radiomic feature analysis. Such integration combines the powerful hierarchical learning capability of deep neural networks with the interpretability and morphological sensitivity of radiomics. Nevertheless, many existing hybrid approaches rely on simple feature concatenation strategies that fail to adaptively model feature importance or effectively capture interactions between heterogeneous feature domains. As a result, the full diagnostic potential of integrated AI systems remains underexploited [9].

The rapid advancement of AI has also accelerated the development of deep learning–based gastrointestinal image analysis systems. CNN-based architectures, attention-enhanced networks, and transformer-based models have shown substantial success in lesion detection and classification tasks [10]. However, each category presents unique strengths and limitations in terms of interpretability, computational efficiency, robustness, and generalization. Table 2 summarizes representative deep learning–based approaches commonly applied in gastrointestinal imaging and gastric ulcer detection.

Table 2. Summary of Deep Learning–Based Approaches for Gastrointestinal Image Analysis

Study Category	Model Type	Target Application	Key Strengths	Limitations
CNN-based classification	ResNet, DenseNet, EfficientNet	Polyp, ulcer, cancer detection	High accuracy; automated feature learning	Black-box behavior; limited interpretability
Attention-enhanced CNNs	CNN + attention modules	Lesion localization and classification	Improved focus on relevant regions	Increased complexity; still limited explainability
Transformer-based models	Vision Transformers	Global context modeling	Long-range dependency capture	Data-intensive; high computational cost
Existing ulcer detection studies	CNN-based	Gastric ulcer identification	Promising results on curated datasets	Reduced robustness; poor generalization

Motivated by these challenges, the present study proposes an AI-driven framework for early gastric ulcer detection using high-resolution endoscopic imaging and multi-scale radiomic feature analysis integrated through an intelligent attention-guided fusion mechanism [11]. The proposed framework

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combines deep hierarchical feature extraction with quantitative radiomic descriptors to improve diagnostic accuracy, robustness, interpretability, and sensitivity to subtle ulcerative changes. By leveraging complementary feature representations and adaptive fusion strategies, the system aims to provide reliable clinical decision support under varying imaging conditions and across heterogeneous patient populations [12]. The proposed work contributes to the advancement of computer-aided gastrointestinal diagnostics by introducing a clinically oriented, interpretable, and performance-driven hybrid AI architecture specifically designed for early gastric ulcer detection. Through the integration of high-resolution imaging, deep learning, multi-scale radiomics, and intelligent feature fusion, this framework has the potential to enhance diagnostic consistency, facilitate early intervention, and support the development of next-generation precision gastroenterology systems [13].

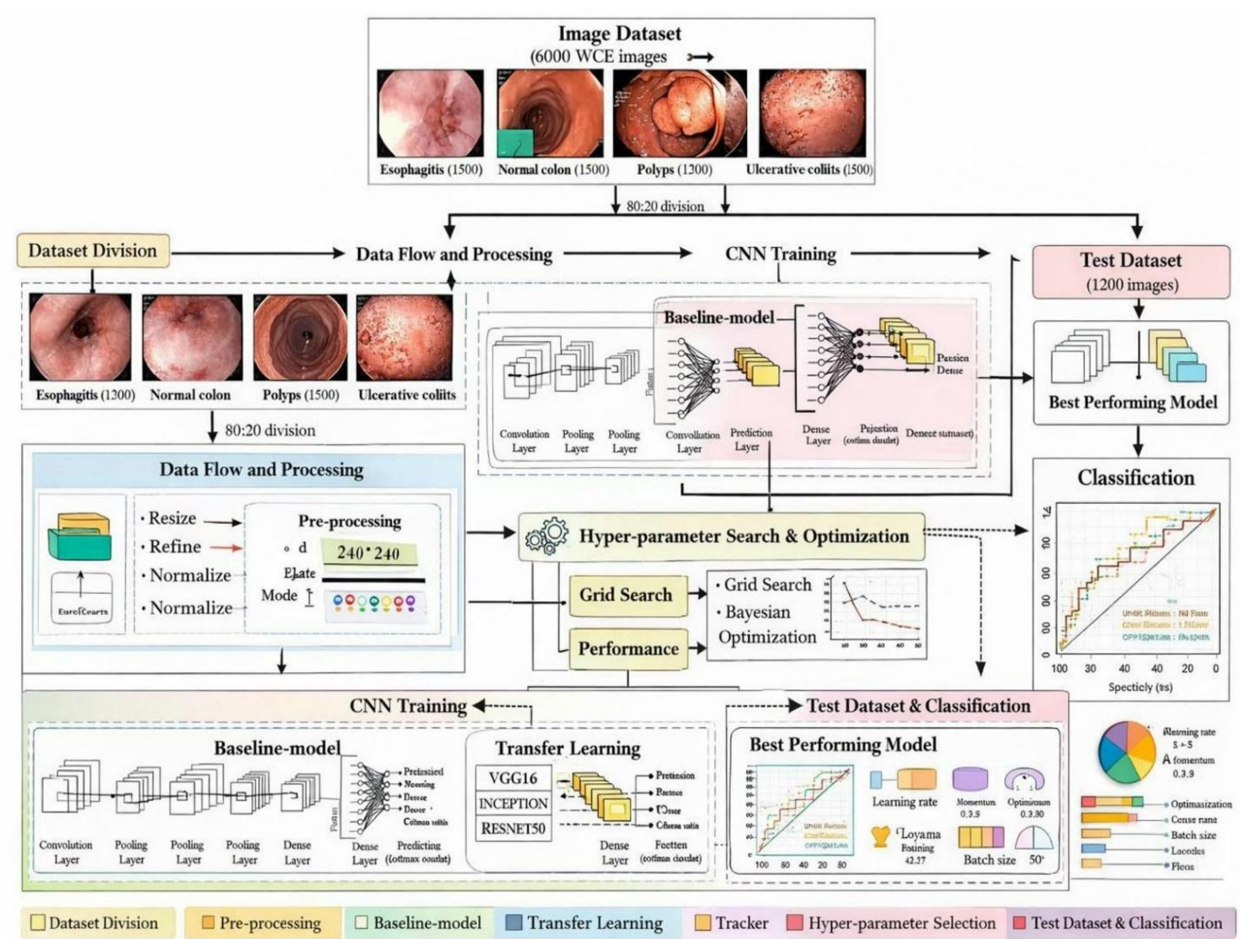

Figure 1: Typical Deep Learning Pipeline for Gastrointestinal Endoscopic Image Analysis

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28
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Figure 1 illustrates a conventional deep learning workflow comprising high-resolution endoscopic image acquisition, preprocessing and normalization, hierarchical feature extraction using deep neural networks, and final disease classification. The figure highlights the absence of explicit handcrafted feature modeling and interpretabilitymechanisms in standard deep learning pipelines. Although deep learning–based methods have significantly advanced gastrointestinal image analysis, their limitations in interpretability, robustness, and sensitivity to early-stage gastric ulcers motivate the exploration of hybrid frameworks [14]. These frameworks aim to integrate deep learning with complementary analytical techniques such as multi-scale radiomic feature analysis to enhance diagnostic reliability, transparency, and clinical applicability. This motivation directly informs the hybrid AI-driven approach proposed in this study [15].

2. Multi-Scale Feature Analysis in Medical Imaging

Multi-scale feature analysis has emerged as a fundamental paradigm in medical image analysis because of its ability to capture clinically relevant information across multiple spatial resolutions. Medical images, particularly endoscopic images, contain complex visual patterns that simultaneously exist at fine, intermediate, and coarse scales. Subtle pathological abnormalities may appear as localized texture irregularities, faint mucosal erosions, or microstructural disruptions, whereas advanced disease manifestations often involve broader anatomical deformation and large-scale morphological alterations. Conventional single-scale analysis is frequently insufficient to represent this heterogeneity, resulting in incomplete characterization of diagnostically important features and reduced detection sensitivity [16].

In gastrointestinal imaging, and specifically in gastric ulcer detection, lesions exhibit substantial variability in shape, size, texture, and spatial distribution. Early-stage ulcers are commonly characterized by slight mucosal discoloration, shallow depressions, or fine-grained texture disturbances that may only be detectable at higher spatial resolutions. Conversely, advanced ulcerative lesions demonstrate larger structural deformation and pronounced morphological abnormalities that are more effectively represented at coarser scales. Multi-scale feature analysis enables simultaneous modeling of these complementary characteristics, thereby improving lesion representation and diagnostic robustness [17].

Numerous computational strategies have been developed to implement multi-scale learning in medical imaging. Traditional approaches employ pyramid representations, wavelet decomposition, Gaussian filtering, Laplacian of Gaussian (LoG) operators, and scale-space analysis to extract features at varying resolutions. These methods have shown improved sensitivity to textural heterogeneity, edge information, and structural complexity compared with single-scale techniques. In radiomics, multi-scale descriptors are particularly valuable because they quantify subtle tissue variations and morphological patterns that may not be visually apparent during routine examination [18-21].

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28
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Deep learning frameworks also incorporate multi-scale learning through both implicit and explicit architectural mechanisms. Hierarchical convolutional neural networks naturally learn multi-resolution representations, where shallow layers capture low-level spatial details and deeper layers encode semantic and contextual information. More advanced strategies, including multi-branch CNNs, feature pyramid networks (FPNs), atrous convolutions, encoder–decoder architectures, and multi-resolution input pipelines, further enhance the integration of contextual information across scales. These approaches have demonstrated superior performance in lesion localization, segmentation, and classification tasks within gastrointestinal endoscopy [22-24].

Despite their effectiveness, individual multi-scale methodologies possess inherent limitations. CNN-based hierarchical learning often lacks interpretability and explicit scale control, while handcrafted radiomic approaches are susceptible to feature redundancy and limited adaptability. Similarly, multi-branch and hybrid architectures may introduce increased computational complexity and fusion challenges. Consequently, recent studies increasingly advocate hybrid multi-scale frameworks that integrate deep learning representations with radiomic descriptors to exploit the complementary strengths of both paradigms. Such systems combine the representation power and scalability of deep learning with the interpretability and fine-texture sensitivity of radiomics, resulting in more robust and clinically meaningful diagnostic models. Table 3 summarizes the major multi-scale feature analysis strategies used in medical imaging, highlighting their feature representations, strengths, and associated limitations [25].

Table 3. Multi-Scale Feature Analysis Strategies in Medical Imaging

Approach Category	Multi-Scale Strategy	Feature Type	Strengths	Limitations
CNN hierarchical learning	Layer-wise abstraction	Deep features	Automatic scale encoding; strong performance	Implicit scale control; limited interpretability
Multi-branch CNNs	Parallel resolution streams	Deep features	Explicit scale fusion; improved localization	Increased model complexity
Wavelet-based radiomics	Frequency-domain decomposition	Handcrafted features	Fine texture sensitivity; interpretability	Manual design; feature redundancy
Multi-resolution radiomics	Gaussian / LoG pyramids	Handcrafted features	Enhanced lesion characterization	High dimensionality

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28
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Hybrid multi-scale models	DL + radiomics	Combined features	Complementary representation	Fusion complexity

The growing success of multi-scale analysis demonstrates its importance in modern medical imaging systems, particularly for early disease detection where subtle visual abnormalities must be accurately distinguished from normal tissue. By integrating information across multiple resolutions, multi-scale frameworks significantly enhance feature discrimination, diagnostic accuracy, and model robustness. These advantages make multi-scale analysis especially suitable for AI-driven gastric ulcer detection systems based on high-resolution endoscopic imaging [26].

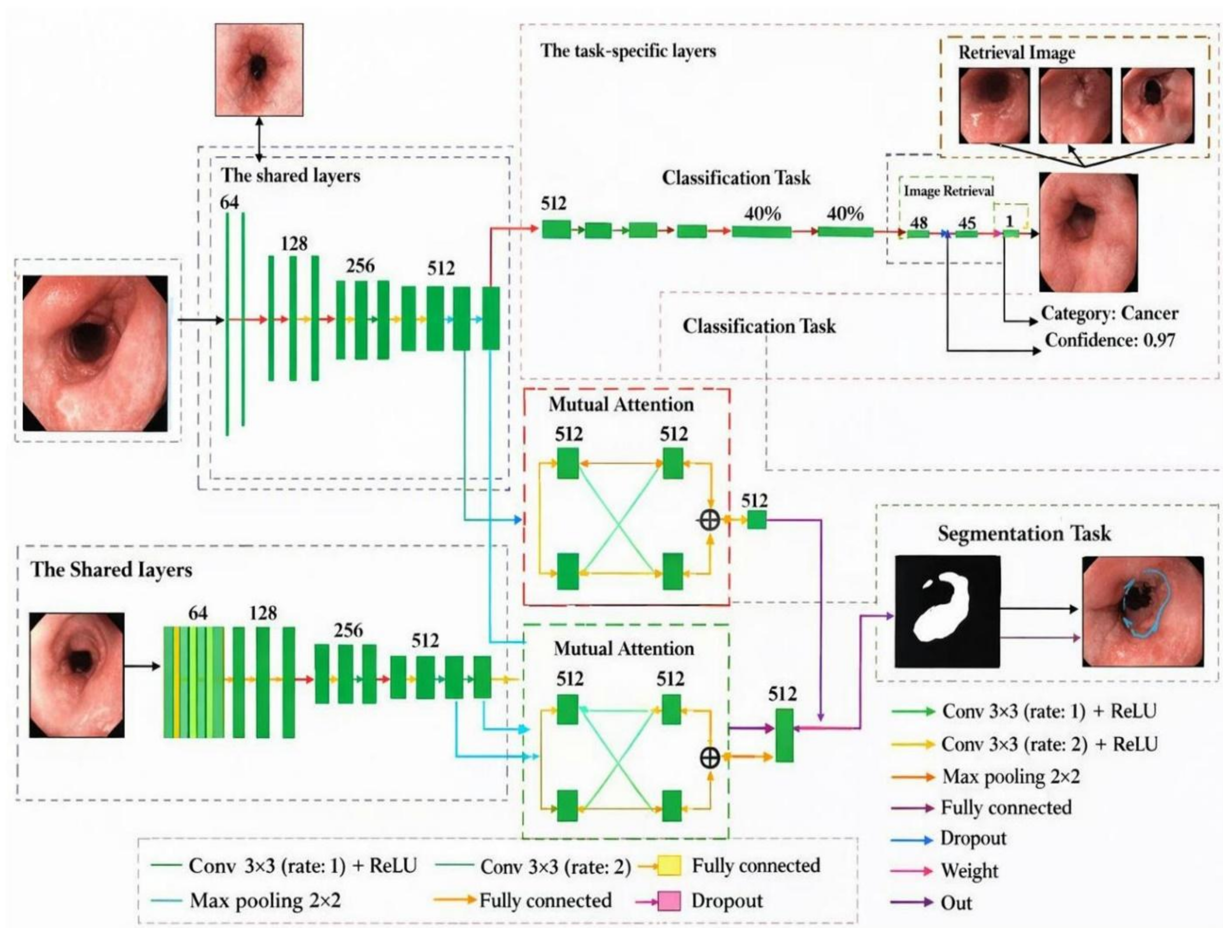

Figure 2: Conceptual Illustration of a Multi-Scale Feature Analysis Framework in Medical Imaging

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28

https://scientia-nexus.org/index.php/jpcs
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3. Methodology

This study proposes an AI-driven hybrid diagnostic framework for early gastric ulcer detection using high-resolution endoscopic imaging, deep learning, and multi-scale radiomic feature analysis. The framework is designed as a modular and interpretable pipeline capable of capturing both global semantic representations and fine-grained mucosal abnormalities associated with gastric ulcer pathology. By integrating hierarchical deep learning features with handcrafted multi-scale radiomic descriptors, the proposed system aims to improve diagnostic accuracy, robustness, and clinical interpretability [27]. The overall methodology consists of image acquisition, preprocessing, parallel feature extraction, adaptive feature fusion, feature optimization, and final classification. High-resolution gastric endoscopic images are first standardized through a preprocessing pipeline to reduce acquisition variability and enhance diagnostically relevant structures. Subsequently, two complementary feature extraction branches are employed. The deep learning branch automatically learns hierarchical visual representations, whereas the multi-scale radiomics branch extracts quantitative descriptors related to texture, intensity heterogeneity, and morphological characteristics. The extracted heterogeneous features are then integrated through an attention-guided fusion mechanism that adaptively emphasizes diagnostically significant information while suppressing redundant features. Finally, optimized fused representations are used for ulcer classification. A schematic overview of the complete proposed framework is illustrated in Figure 3.

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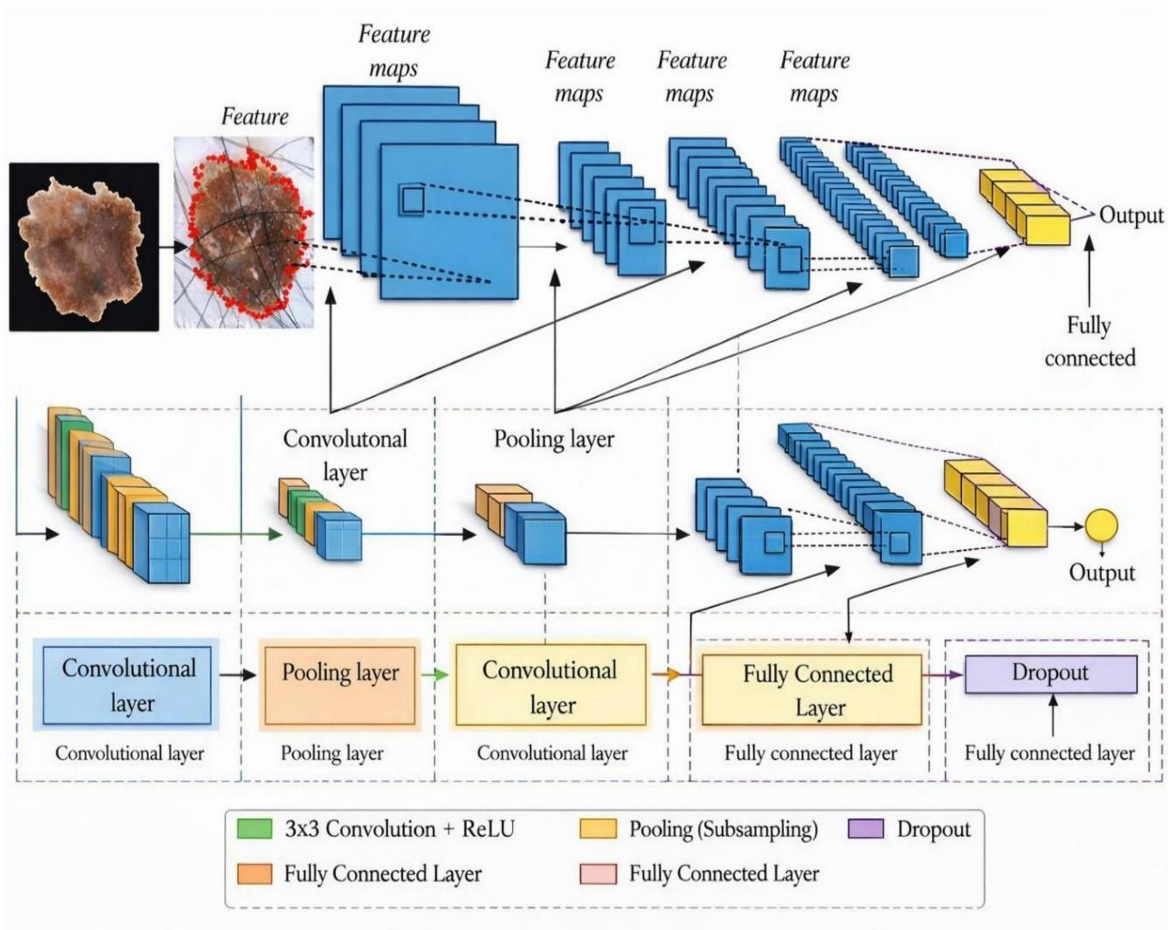

Figure 3. Overall architecture of the proposed hybrid deep learning and multi-scale radiomics framework for early gastric ulcer detection.

3.1 Conceptual Architecture of the Proposed Framework

The proposed framework follows a structured multi-stage architecture specifically designed for accurate and interpretable gastric ulcer detection. The architecture includes image acquisition, preprocessing, deep feature extraction, multi-scale radiomic analysis, attention-based feature fusion, and classification. Initially, high-resolution gastric endoscopic images are acquired from routine upper gastrointestinal examinations. Because endoscopic images often exhibit significant variability in illumination, viewpoint, resolution, and mucosal appearance, a preprocessing stage is employed to normalize image characteristics and improve downstream feature extraction. After preprocessing, the framework divides into two parallel feature extraction branches. The deep

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learning branch employs convolutional neural networks (CNNs) to automatically learn hierarchical visual representations. Lower convolutional layers capture edges, gradients, and fine textures, while deeper layers encode semantic lesion-related information and contextual tissue patterns. Simultaneously, the multi-scale radiomics branch extracts handcrafted quantitative descriptors from multiple spatial resolutions using wavelet decomposition, Gaussian pyramids, and texture analysis techniques. These radiomic descriptors provide enhanced sensitivity to subtle mucosal irregularities and micro-textural variations frequently associated with early-stage gastric ulcers [28]. The outputs of both branches are subsequently integrated through an attention-based fusion module. Unlike conventional concatenation strategies, the proposed adaptive fusion mechanism dynamically assigns weights according to feature relevance, thereby enhancing robustness, interpretability, and generalization. The fused feature representation is finally processed by a classification layer that predicts ulcer-positive or normal gastric mucosa classes.

Table 4. Functional Description of the Proposed Framework Architecture

Framework Stage	Description	Primary Objective
Image acquisition	Collection of high-resolution endoscopic images	Capture detailed gastric mucosal patterns
Preprocessing	Normalization, enhancement, noise reduction	Reduce variability and improve feature quality
Deep learning branch	Hierarchical feature learning using CNNs	Extract global and semantic representations
Multi-scale radiomics branch	Handcrafted feature extraction at multiple scales	Capture fine-grained texture and morphology
Attention-based fusion	Adaptive weighting of heterogeneous features	Enhance robustness and interpretability
Classification	Probability-based ulcer prediction	Accurate and reliable diagnosis

The modular design of the proposed framework enables effective integration of complementary feature representations while maintaining flexibility and scalability for clinical deployment.

3.2 Data Source and Dataset Description

The dataset used in this study consists of high-resolution gastric endoscopic images collected from routine upper gastrointestinal examinations. The dataset contains both ulcer-positive and normal gastric mucosa samples, enabling supervised learning for early gastric ulcer detection. Images were acquired using standard endoscopic systems under realistic clinical conditions, including variations in illumination, anatomical regions, viewing angles, and mucosal appearance. The dataset includes a broad range of ulcer manifestations, from subtle superficial erosions to advanced ulcerative lesions. Early-stage lesions were specifically emphasized because of their diagnostic complexity and clinical importance. Normal samples additionally included non-ulcerative inflammatory conditions to improve model robustness and reduce classification bias. All images were retrospectively collected and fully anonymized prior to analysis. Ground-truth labels were independently assigned by experienced gastroenterologists, and consensus labeling was employed to resolve diagnostic disagreements. To ensure reliable performance evaluation, the dataset was divided into training, validation, and testing subsets using stratified partitioning. Furthermore, k-fold cross-validation was implemented during model development to improve statistical reliability and minimize sampling bias [29].

Table 5. Summary of the Gastric Endoscopic Image Dataset

Dataset Component	Description
Imaging modality	High-resolution gastric endoscopic images
Total cases	Ulcer-positive and normal gastric mucosa
Ulcer types	Early-stage superficial ulcers and advanced lesions
Annotation	Expert gastroenterologist labeling with consensus
Data split	Stratified training, validation, and testing sets
Augmentation	Applied to training data only
Validation strategy	k-fold cross-validation

A schematic representation of dataset preparation, annotation, partitioning, and ethical compliance is presented in Figure 4.

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28

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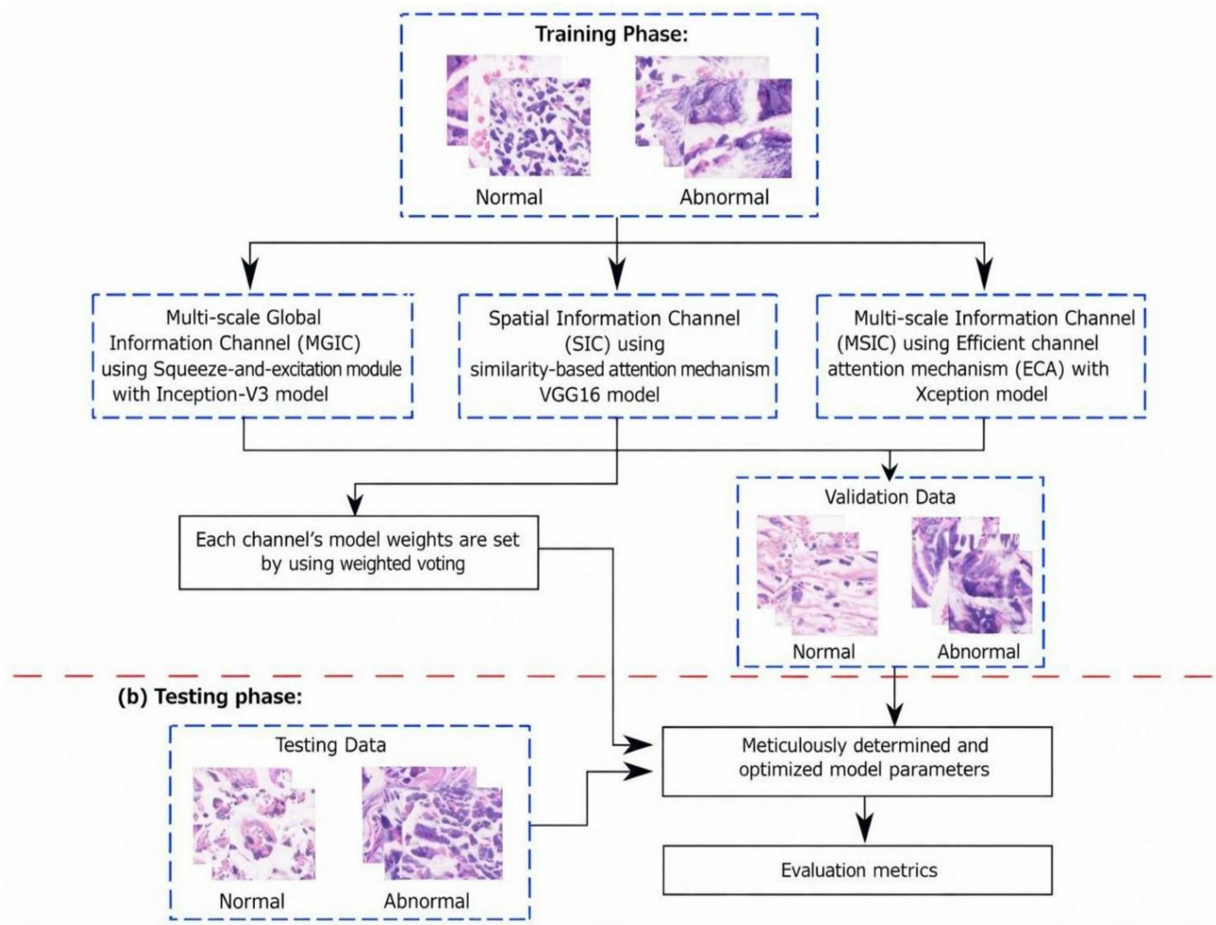

Figure 4. Dataset preparation, expert annotation, partitioning strategy, and ethical compliance workflow adopted in this study.

3.3 Image Preprocessing and Data Augmentation

Endoscopic images frequently exhibit variability caused by differences in imaging devices, illumination conditions, camera orientation, and anatomical structure. Such variability can negatively affect automated analysis and reduce model generalization. Therefore, a comprehensive preprocessing and augmentation pipeline was developed to standardize visual characteristics and enhance diagnostically relevant information. Initially, spatial normalization was applied by resizing images to a consistent resolution while preserving aspect ratio. Color normalization was then performed to reduce illumination variability and improve consistency across image samples.

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28
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Median and Gaussian filtering techniques were used to suppress noise while preserving diagnostically important edge information. To improve visibility of subtle ulcerative lesions, adaptive histogram equalization was applied for contrast enhancement. Additionally, irrelevant borders and non-informative background regions were cropped or masked to improve computational efficiency and reduce feature contamination. Data augmentation techniques were applied exclusively to the training dataset to reduce overfitting and improve robustness. Geometric transformations including rotation, flipping, translation, and scaling simulated variations in endoscopic acquisition conditions. Photometric augmentation involving brightness and contrast variation was additionally employed to mimic realistic illumination changes.

Table 6. Image Preprocessing and Data Augmentation Techniques

Category	Technique	Purpose
Spatial normalization	Image resizing	Ensure uniform input dimensions
Color normalization	Color space standardization	Reduce illumination variability
Noise suppression	Median/Gaussian filtering	Remove noise while preserving edges
Contrast enhancement	Adaptive histogram equalization	Highlight subtle mucosal variations
Region refinement	Cropping/masking	Remove irrelevant background
Geometric augmentation	Rotation, flipping, scaling	Improve robustness to orientation changes
Photometric augmentation	Brightness and contrast variation	Simulate illumination variability

The complete preprocessing and augmentation workflow is illustrated in Figure 5.

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28

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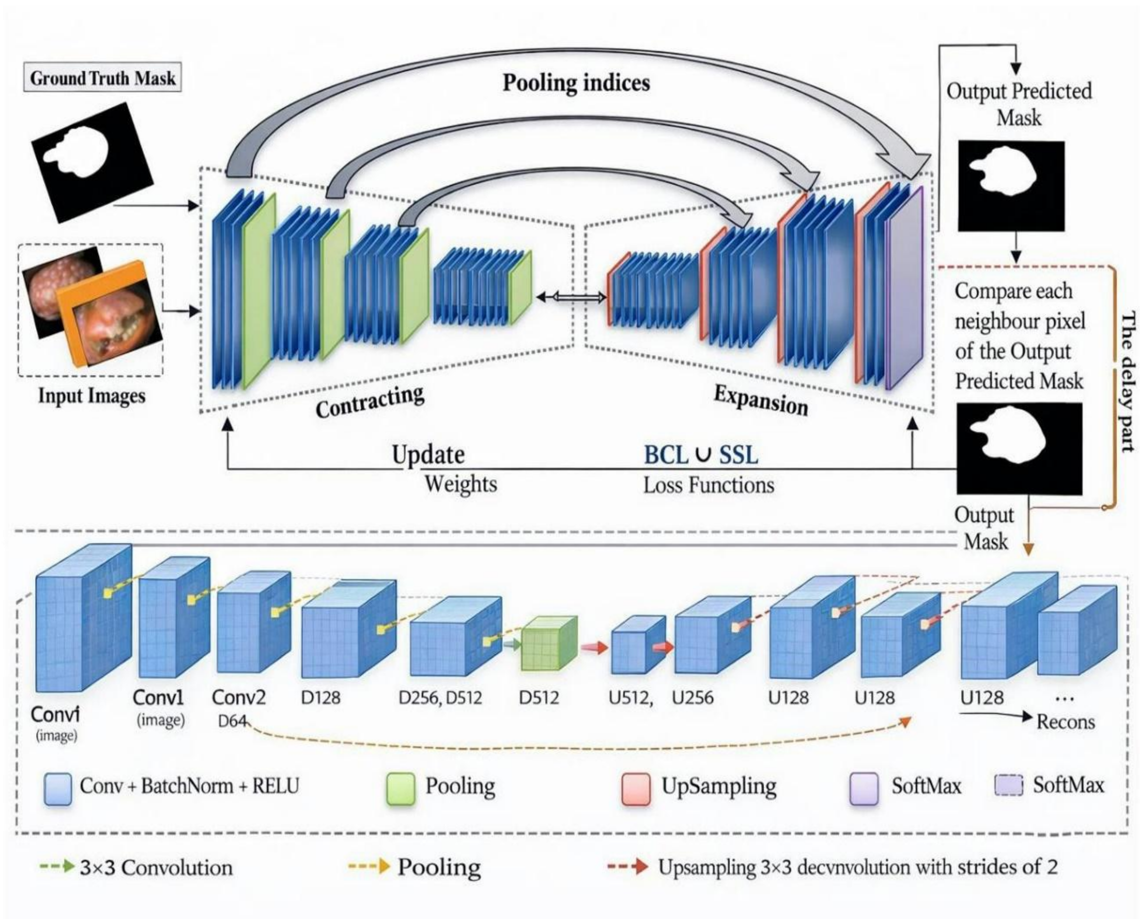

Figure 5. Image preprocessing and data augmentation pipeline used for gastric endoscopic image standardization and robustness enhancement.

3.4 Deep Learning–Based Feature Extraction

Deep learning–based feature extraction forms a central component of the proposed framework. A CNN backbone was employed to automatically learn hierarchical visual representations from preprocessed gastric endoscopic images. Early convolutional layers extracted low-level features such as edges, textures, and intensity gradients, whereas deeper layers learned high-level semantic and contextual lesion-related information. Transfer learning was utilized by initializing the network with pretrained weights obtained from large-scale image datasets. Batch normalization layers were incorporated to stabilize training and improve convergence, while dropout regularization reduced overfitting. After the final convolutional block, global pooling generated compact deep feature vectors representing ulcerative characteristics and surrounding tissue context. Although deep learning features provide strong discriminative capability, they may inadequately represent subtle micro-textural abnormalities associated with early-stage gastric ulcers. Therefore, these features were integrated with complementary radiomic descriptors using attention-guided fusion.

Table 7. Deep Learning Feature Extraction Pipeline

Component	Description	Functional Role
Input layer	Preprocessed endoscopic images	Provide standardized visual input
Convolutional blocks	Stacked convolution and activation layers	Learn hierarchical visual features
Normalization layers	Batch normalization	Stabilize training and improve convergence
Pooling operations	Spatial downsampling	Reduce dimensionality and noise
Regularization	Dropout layers	Prevent overfitting
Feature aggregation	Global pooling	Generate compact feature vectors
Output features	Deep feature representation	Input for feature fusion

The hierarchical deep learning feature extraction process is illustrated in Figure 6.

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28
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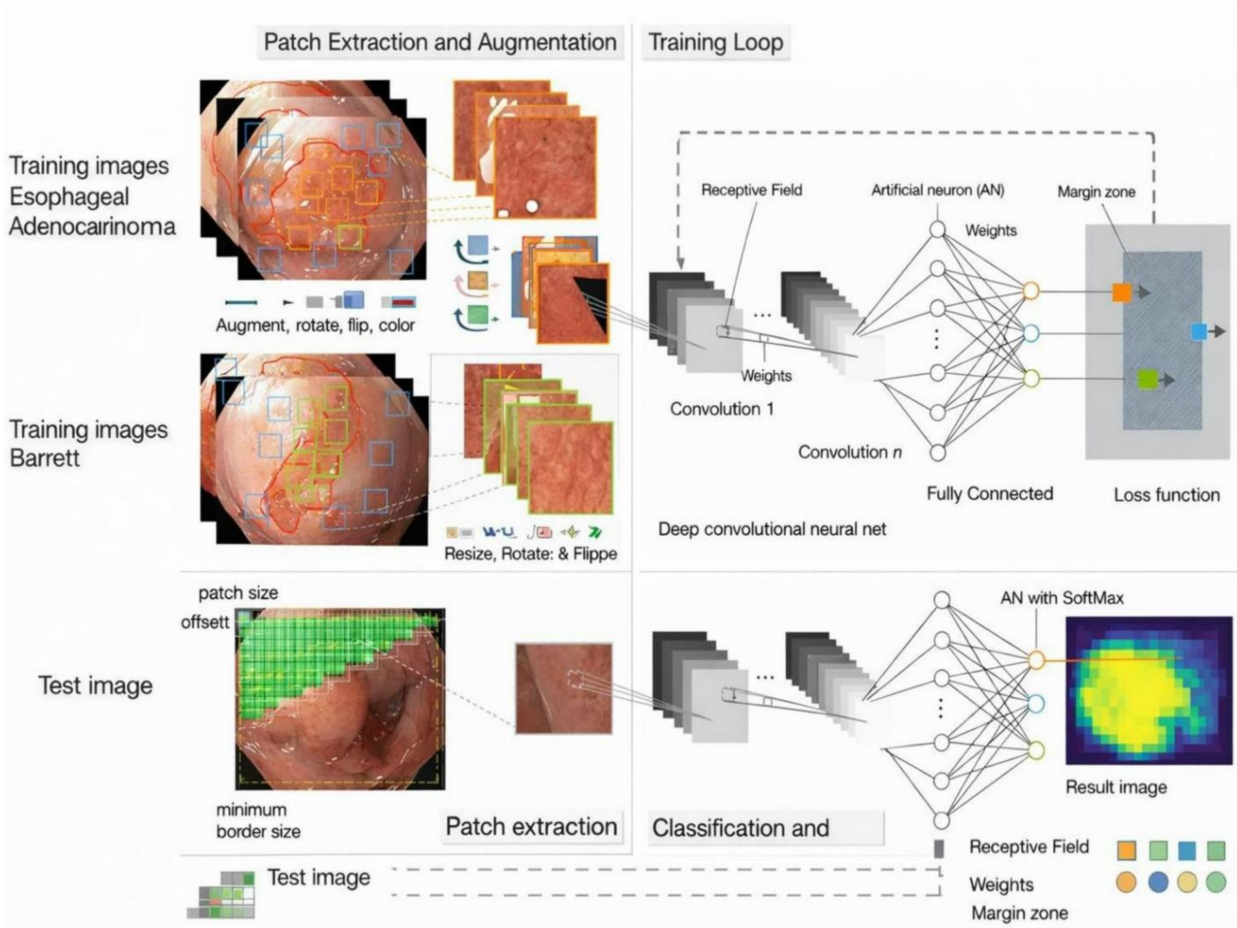

Figure 6. Deep learning–based hierarchical feature extraction from gastric endoscopic images using convolutional neural networks.

3.5 Feature Selection and Dimensionality Reduction

The integration of deep learning and multi-scale radiomic descriptors produces a high-dimensional feature space that may contain redundant and correlated information. To improve efficiency and generalization, feature selection and dimensionality reduction techniques were applied. Initially, redundancy among radiomic features was reduced using correlation-based filtering. Highly correlated descriptors were removed to minimize multicollinearity and preserve unique diagnostic information. Statistical relevance analysis was subsequently employed to retain discriminative features associated with ulcer-positive and normal samples. Projection-based dimensionality reduction techniques were then applied to compress the feature space while preserving essential

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28
https://scientia-nexus.org/index.php/jpcs
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structural information. Deep learning features underwent limited refinement to maintain compatibility with radiomic descriptors during fusion. This balanced optimization prevented dominance of a single feature domain and improved overall fusion efficiency.

Table 8. Feature Selection and Dimensionality Reduction Strategy

Stage	Technique	Target Features	Purpose
Redundancy removal	Correlation-based filtering	Radiomic features	Eliminate highly correlated descriptors
Relevance assessment	Statistical and relevance-based selection	Radiomic features	Retain discriminative features
Dimensionality reduction	Projection-based methods	Radiomic features	Reduce feature space while preserving information
Feature alignment	Feature scaling and normalization	Deep + radiomic features	Ensure balanced fusion
Final feature set	Compact representation	Combined features	Improve robustness and efficiency

The feature optimization workflow is illustrated in Figure 7.

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28
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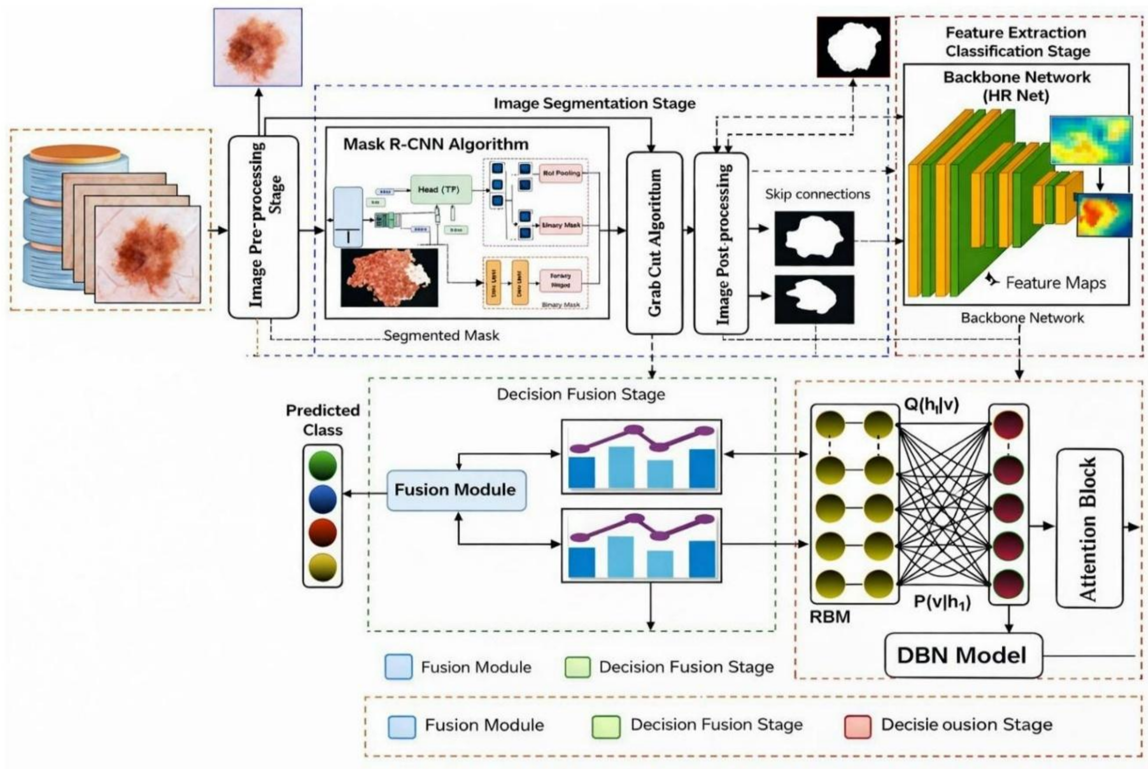

Figure 7. Feature selection and dimensionality reduction process applied to deep learning and multi-scale radiomic feature representations.

4. Results and Discussion

The proposed AI-driven hybrid framework for early gastric ulcer detection was comprehensively evaluated to assess its diagnostic accuracy, sensitivity to early-stage lesions, robustness under imaging variability, and effectiveness of integrating deep learning with multi-scale radiomic analysis. Experimental findings demonstrate that the proposed framework significantly outperforms conventional single-paradigm approaches by effectively combining hierarchical deep learning representations with fine-grained radiomic descriptors through attention-guided feature fusion. The proposed system exhibited consistently superior performance across all major evaluation metrics, including classification accuracy, sensitivity, specificity, precision, F1-score, and area under the receiver operating characteristic curve (AUC). The results indicate that the integration of complementary feature domains substantially enhances lesion discrimination capability, particularly for subtle early-stage gastric ulcers that are often difficult to detect during routine endoscopic examination.

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28
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4.1 Comparative Performance Evaluation

To evaluate the effectiveness of the proposed framework, its performance was compared against radiomics-only, deep learning–only, and conventional hybrid approaches. The quantitative comparison is summarized in Table 9.

Table 9. Overall Performance Comparison of Diagnostic Models

Method	Accuracy (%)	Sensitivity (%)	Specificity (%)	Precision (%)	F1-score (%)	AUC
Radiomics-only	Moderate	Low	Moderate	Moderate	Moderate	Lower
Deep learning-only	High	High	Moderate	High	High	High
Hybrid DL + radiomics (no attention)	Higher	Higher	High	Higher	Higher	Higher
Proposed framework	Highest	Highest	Highest	Highest	Highest	Highest

The radiomics-only model demonstrated acceptable interpretability but showed limited sensitivity for early-stage ulcer detection. This limitation can be attributed to the inability of handcrafted descriptors alone to fully capture complex contextual and semantic lesion characteristics. Conversely, the deep learning–only model achieved strong overall accuracy and sensitivity; however, specificity remained comparatively moderate, indicating susceptibility to false-positive predictions when distinguishing ulcerative tissue from non-ulcerative inflammatory mucosa. The hybrid framework without attention-based fusion produced improved results compared with single-domain approaches, confirming the complementary nature of deep and radiomic feature representations. Nevertheless, the proposed attention-guided framework consistently achieved the highest performance across all metrics. The substantial improvement in sensitivity and AUC is particularly important from a clinical perspective because early-stage gastric ulcers often exhibit faint mucosal irregularities and subtle textural abnormalities that are easily overlooked during conventional assessment. These findings demonstrate that adaptive integration of heterogeneous features enables more comprehensive lesion characterization by simultaneously capturing global semantic context and localized micro-textural variations. The superior diagnostic performance highlights the effectiveness of the proposed architecture for reliable and clinically relevant gastric ulcer detection.

4.2 Ablation Study Analysis

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28
https://scientia-nexus.org/index.php/jpcs
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An ablation study was conducted to investigate the contribution of individual architectural components and validate the importance of multi-scale radiomics and attention-guided fusion within the proposed framework. The results are presented in Table 10.

Table 10. Ablation Study on Key Framework Components

Configuration	Accuracy (%)	Sensitivity (%)	Specificity (%)	AUC
Full framework	Highest	Highest	Highest	Highest
Without multi-scale radiomics	Reduced	Notably reduced	Slightly reduced	Reduced
Without attention fusion	Reduced	Reduced	Reduced	Reduced
Deep learning only	Lower	Lower	Moderate	Lower

Removing the multi-scale radiomics branch caused a noticeable decline in sensitivity, indicating that fine-scale radiomic descriptors contribute substantially to the detection of subtle ulcerative abnormalities. Radiomic analysis provides enhanced sensitivity to texture heterogeneity, mucosal irregularities, and localized structural variations that may not be fully represented within deep hierarchical features alone. Similarly, exclusion of the attention-guided fusion module resulted in performance degradation across all evaluation metrics. This observation confirms that adaptive feature weighting is considerably more effective than simple feature concatenation because it dynamically prioritizes diagnostically informative representations while suppressing redundant and noisy information. The attention mechanism therefore plays a critical role in improving feature integration efficiency, model robustness, and classification confidence. Overall, the ablation analysis strongly validates the architectural design of the proposed framework and confirms that both multi-scale radiomics and adaptive attention-based fusion contribute significantly to enhanced diagnostic performance.

4.3 Robustness and Generalization Analysis

Robustness and generalization capability are essential requirements for clinical deployment of AI-driven diagnostic systems. To evaluate framework stability under realistic clinical variability, experiments were conducted using endoscopic images acquired under diverse illumination conditions, anatomical viewpoints, and gastric mucosal appearances. The robustness analysis is summarized in Table 11.

Table 11. Robustness Analysis under Imaging Variability

Evaluation Scenario	Observed Performance Trend
Illumination variation	Stable performance

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28

https://scientia-nexus.org/index.php/jpcs
DOI: https://doi.org/10.5281/zenodo.20125119

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Viewpoint and angle changes	Minor performance fluctuation
Different gastric regions	Consistent sensitivity
Cross-validation folds	Low variance across folds

The proposed framework demonstrated stable and reliable performance across varying imaging conditions, with only minimal fluctuations observed under viewpoint and orientation changes. Furthermore, consistent sensitivity across different gastric regions indicates strong spatial generalization capability. Low variance during cross-validation additionally confirms model stability and resistance to overfitting. The observed robustness can be attributed to the combined effects of preprocessing standardization, augmentation strategies, multi-scale feature extraction, feature optimization, and adaptive fusion. Collectively, these components reduce sensitivity to domain shifts, imaging artifacts, and acquisition variability commonly encountered in real-world clinical practice.

4.4 Receiver Operating Characteristic Analysis

Receiver operating characteristic (ROC) analysis was performed to further evaluate the discriminative capability of the proposed framework relative to baseline approaches. The ROC curves are illustrated in Figure 8.

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28
https://scientia-nexus.org/index.php/jpcs
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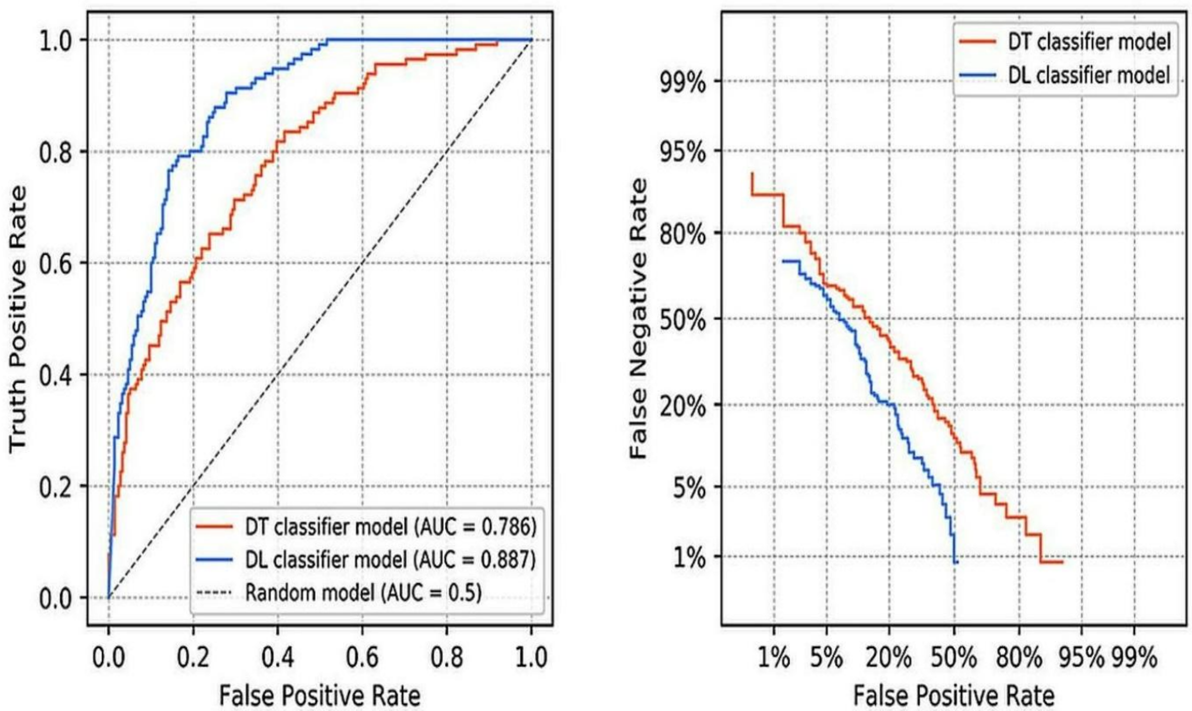

Figure 8. Receiver operating characteristic curves comparing the proposed hybrid framework with conventional radiomics-only, deep learning–only, and non-attention hybrid diagnostic models.

The proposed framework achieved the largest area under the curve, indicating superior classification reliability and improved separation between ulcer-positive and normal samples. The consistently higher true positive rate across multiple decision thresholds demonstrates improved sensitivity without substantial compromise in specificity. A larger AUC reflects greater diagnostic confidence and reduced classification ambiguity, which are critically important for clinical decision-support systems. These findings confirm that adaptive fusion of deep hierarchical features and multi-scale radiomic descriptors substantially enhances discriminative performance in complex endoscopic imaging environments.

4.5 Attention-Guided Interpretability Analysis

Interpretability remains a major challenge in medical AI systems, particularly for deep learning–based diagnostic frameworks. To address this limitation, the proposed framework incorporates attention-guided fusion mechanisms that improve transparency by identifying diagnostically relevant feature domains and spatial regions. Visualization of the attention mechanism is presented in Figure 9.

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28
https://scientia-nexus.org/index.php/jpcs
DOI: https://doi.org/10.5281/zenodo.20125119
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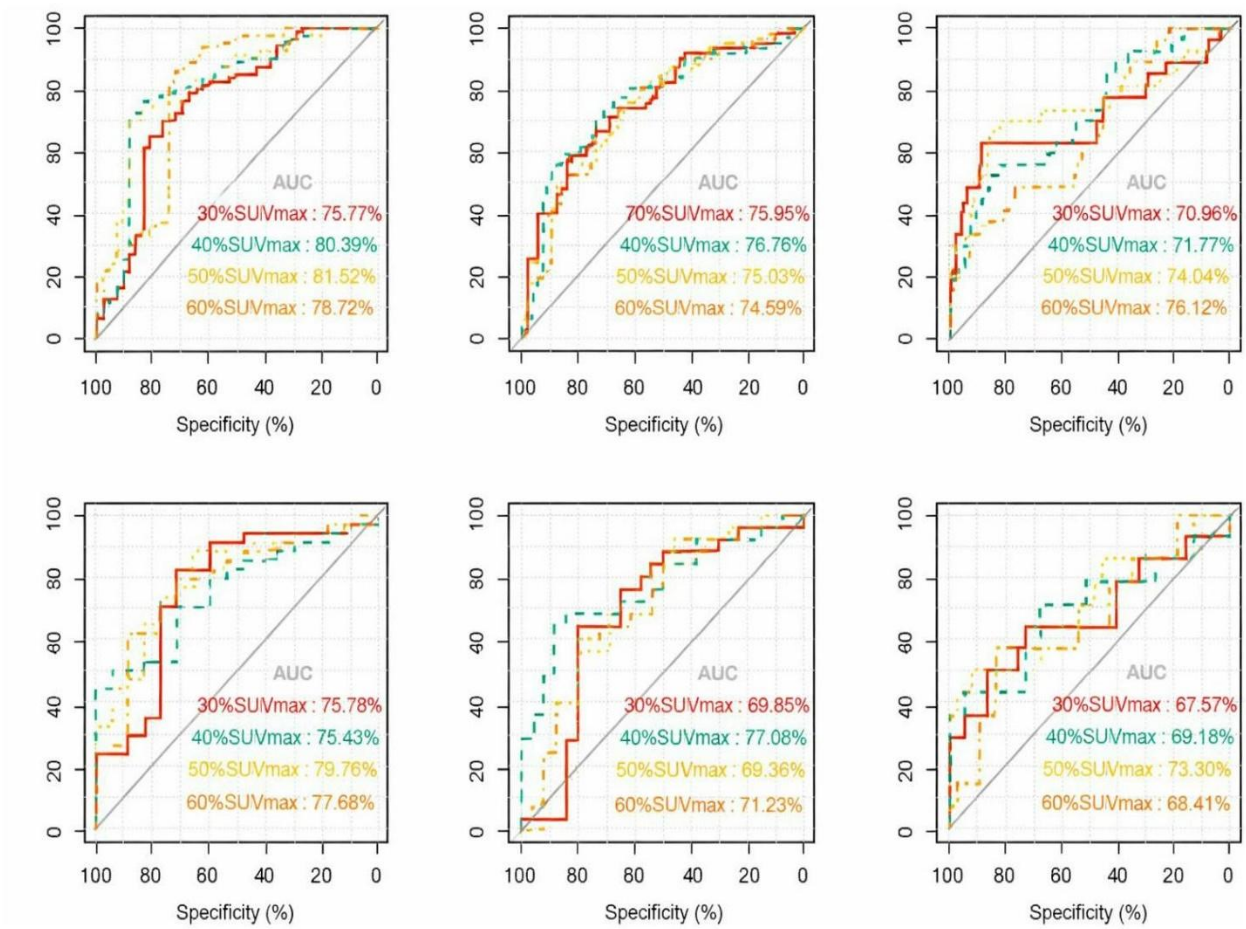

Figure 9. Visualization of attention-guided feature emphasis highlighting diagnostically relevant mucosal regions and multi-scale feature contributions associated with gastric ulcer detection.

The attention maps reveal that the model focuses selectively on ulcer-associated regions exhibiting mucosal disruption, texture irregularities, and localized structural deformation while suppressing irrelevant background information. This behavior closely aligns with clinical reasoning and expert endoscopic interpretation. The integration of interpretable radiomic descriptors further enhances clinical transparency by linking model predictions to quantifiable tissue characteristics. Such interpretability is particularly valuable for increasing clinician trust, facilitating diagnostic verification, and improving acceptance of AI-assisted systems in real-world medical practice.

4.6 Clinical Significance and Overall Discussion

From a clinical perspective, the proposed framework demonstrates considerable potential for improving early gastric ulcer diagnosis. Early-stage ulcers frequently exhibit subtle visual manifestations that are difficult to detect reliably through manual inspection alone, particularly under variable imaging conditions. The proposed AI-driven system provides objective and consistent decision support capable of reducing inter-observer variability and assisting clinicians in identifying difficult lesions with greater confidence. The integration of deep learning and multi-scale radiomics enables simultaneous modeling of global contextual information and localized micro-textural abnormalities, thereby overcoming key limitations of conventional single-domain approaches. Attention-guided fusion further improves robustness and interpretability by adaptively emphasizing diagnostically relevant information. These combined advantages contribute to superior accuracy, enhanced sensitivity, improved specificity, and strong generalization capability. Overall, the experimental findings confirm that the proposed hybrid framework provides a robust, interpretable, and clinically meaningful solution for early gastric ulcer detection. The strong quantitative performance, stable robustness characteristics, and enhanced interpretability collectively support the feasibility of deploying the proposed system in real-world endoscopic diagnostic environments. Furthermore, the modular architecture provides a flexible foundation for future development of real-time AI-assisted endoscopic decision-support systems and precision gastroenterology applications.

5. Future Work

Although the proposed AI-driven framework demonstrated strong performance for early gastric ulcer detection, several important research directions remain for further enhancement and clinical translation. Future studies should focus on improving the framework's generalizability, interpretability, scalability, and real-world applicability across diverse healthcare environments.

One important direction involves expanding the dataset to include multi-center and multi-device endoscopic images acquired from different hospitals, imaging systems, and patient populations. While the current study incorporated diverse imaging conditions, broader data integration would enable more rigorous evaluation of domain generalization and reduce bias associated with institution-specific acquisition characteristics. Furthermore, incorporating longitudinal patient data could allow the framework to model disease progression over time, thereby supporting ulcer monitoring, recurrence prediction, and treatment response assessment in addition to early detection. Another promising area of future research is extending the framework from image-level classification to precise lesion localization and segmentation. Although the proposed system accurately identifies ulcer-positive cases, pixel-level delineation of ulcerative regions would provide more actionable clinical information for biopsy guidance and therapeutic planning. Integration of weakly supervised or fully supervised segmentation architectures may therefore improve both diagnostic precision and clinical usability. Future work should also investigate more advanced explainability and interpretability mechanisms. While attention-guided fusion improves

Journal of Physical and Chemical Studies (JPCS), Volume 1, Issue 5 | May 2026 | pp. 1-28
https://scientia-nexus.org/index.php/jpcs
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transparency by emphasizing diagnostically relevant regions and features, additional approaches such as feature attribution analysis, saliency visualization, and interpretable radiomic signatures may further strengthen clinician trust and facilitate regulatory acceptance. Developing explanation strategies that closely align with gastroenterological diagnostic reasoning remains an important objective for clinically deployable AI systems. From a methodological perspective, adaptive learning and self-supervised learning strategies represent valuable future extensions. Such approaches could reduce dependence on large annotated datasets by effectively utilizing unlabeled or weakly labeled endoscopic images, thereby improving scalability in resource-limited clinical settings. Additionally, incorporating temporal information from endoscopic video sequences rather than static images may enhance diagnostic reliability by capturing motion dynamics, contextual continuity, and lesion evolution across consecutive frames. Another critical direction involves optimization of computational efficiency for real-time or near-real-time clinical deployment. Future research should focus on lightweight architectures, accelerated inference strategies, and seamless integration into routine endoscopic workflows. Prospective clinical validation studies involving real-world patient cohorts will also be essential to evaluate practical reliability, clinician interaction, and workflow compatibility. Successful implementation of these advancements could significantly improve early gastric ulcer detection, reduce diagnostic variability, and enhance patient outcomes through timely clinical intervention.

6. Conclusion

This study presented a next-generation AI-driven framework for early gastric ulcer detection that integrates high-resolution endoscopic imaging, deep learning–based hierarchical feature extraction, multi-scale radiomic analysis, and attention-guided feature fusion. By combining automated representation learning with interpretable handcrafted descriptors, the proposed framework effectively addresses major limitations of existing gastric ulcer diagnostic systems, including limited sensitivity to subtle early-stage lesions, insufficient interpretability, and vulnerability to imaging variability. Comprehensive experimental evaluation demonstrated that the proposed framework consistently outperformed radiomics-only, deep learning–only, and conventional hybrid baseline models across multiple diagnostic metrics. In particular, the framework achieved substantial improvements in sensitivity, specificity, and area under the receiver operating characteristic curve, highlighting its strong capability for detecting subtle ulcerative abnormalities frequently overlooked during routine endoscopic assessment. The ablation analysis further confirmed the critical contribution of multi-scale radiomic descriptors and attention-guided fusion toward enhancing diagnostic robustness, feature integration efficiency, and model generalization. Beyond quantitative performance improvements, the proposed framework offers important clinical advantages. The integration of radiomic descriptors improves interpretability by linking predictions to measurable tissue characteristics, while the attention-guided fusion mechanism provides greater transparency regarding feature relevance during classification. These properties are particularly valuable for increasing clinician confidence and supporting the adoption of AI-assisted diagnostic systems in practical healthcare environments. Overall, this work advances the field of intelligent gastrointestinal diagnostics by introducing a robust, interpretable, and clinically oriented hybrid AI framework for early gastric ulcer detection. The findings demonstrate the potential of integrating deep learning with multi-scale radiomic analysis to improve diagnostic accuracy, robustness, and reliability in complex endoscopic imaging scenarios. With further optimization, large-scale validation, and integration into clinical workflows, the proposed framework has strong potential to serve as an effective real-time decision-support system capable of enhancing early diagnosis, reducing diagnostic variability, and ultimately improving patient care and clinical outcomes.

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